NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1392

ICING ZONES IN A WARM FRONT SYSTEM WITH GENERAL PRECIPITATION

By William Lewis, U. S. Weather Bureau

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Moffett Field, Calif.

Washington
July, 1947

E R R A T U M

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The source of the subject report was inadvertently omitted from the cover and the first page of text. A revised copy of each, reading "By William Lewis, U. S. Weather Bureau," is attached.

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ICING ZONES IN A WARM FRONT SYSTEM WITH GENERAL PRECIPITATION

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SUMMARY

Observation of the icing zones present in a warm front cloud system were made during one of a series of flights designed to investigate the meteorological conditions conducive to the formation of ice on aircraft. While it is realized that it is hazardous to venture general conclusions from observations of a single case, a consistent theoretical interpretation of the observed conditions is believed to justify the conclusion that in large areas of uniform precipitation in the absence of marked orographic effects, the icing zones are limited to the freezing rain area, if any, and a shallow layer of mixed snow and cloud drops just above the freezing level.

INTRODUCTION

The principal meteorological factors which determine icing conditions are temperature, liquid water concentration, and drop size. To study these factors and their relationship to the formation of ice on airplanes, the Ames Aeronautical Laboratory of the National Advisory Committee for Aeronautics has equipped a C-46 cargo airplane with a thermal ice-prevention system and pertinent meteorological instrumentation and is conducting an extensive flight investigation in inclement weather. During the phase of this investigation which was

[1]This report was prepared by Mr. Lewis in collaboration with the staff of the Ames Laboratory during a period of active participation by Mr. Lewis in the NACA icing research program

conducted throughout the winter of 1944-45, a flight was made in a warm front cloud system. While this particular situation was the only well defined warm front encountered during the entire season's operations, it is believed that it was typical of warm sector cyclones having a large area of uniform precipitation. Observations made during this particular flight and a discussion of certain general aspects of the problem of icing in precipitation areas are presented in this report.

OBSERVATIONS

The flight described herein was made in the warm front cloud system which existed over Minnesota on March 15, 1945. Observations made during the flight have been combined with surface and upper air data obtained from the U.S. Weather Bureau to reconstruct the meteorological conditions existing at the time of the flight. Figure 1 is the surface weather map for 9:30 a.m. Central Standard Time on March 15, 1945. A deepening cyclone with an open warm sector was centered about 60 miles southwest of Minneapolis, Minn., moving east northeastward at about 20 miles per hour and deepening at about 0.6 millibar per hour. Rain was falling over most of Minnesota with snow north of the Canadian border. The presence of an area of freezing rain below the warm front surface was indicated by the observation of sleet (U.S. definition) at International Falls, Minn. The average temperature and dew point of air entering the system in the warm sector on a line from Des Moines, Iowa, to Chicago, Ill., were 59° and 53° F, respectively. This air had the same equivalent potential temperature as the air at 5000 feet over Duluth, Minn., indicating that warm sector air was being lifted over the warm front. Precipitation rates were light to moderate, averaging about 0.08 inch per hour over eastern Minnesota.

The cross section (fig. 2), showing the structure of the warm front cloud and precipitation area, was drawn from data taken on the flight and Weather Bureau radiosonde data taken at St. Paul, Minn., and International Falls, Minn. It shows the location of the frontal surface and icing zones, and the approximate distribution of temperature. The radiosonde data are shown in figures 3 and 4. The radiosonde observations were made at 9 a.m., the surface observations are for 9:30 a.m., and the flight obervations covered the interval from 8:24 to 11:45 a.m. The cross section was drawn to represent conditions at about 9:30 a.m.

The flight began at 8:24 a.m. A layer of low scud clouds with tops below 2500 feet was encountered just after take-off, and another cloud layer extended from 3500 to 5000 feet altitude. The airplane was between cloud layers from 5000 feet to 9200 feet in steady rain. The freezing level was reached at an altitude of 9200 feet and by 9500 feet the rain had turned to snow. From 9,500 feet to 19,000 feet the air was uniformly full of falling snow. No liquid water was present and no icing occurred. The climb was terminated at an altitude of 19,000 feet at 9:20 a.m. The elevation of the top of the snow cloud is unknown and the presence or absence of a layer of liquid water drops in the top of the cloud formation could not be determined. The temperature-height curve for this part of the flight is shown in figure 5.

The airplane then descended to an altitude of 9000 feet. A trace of clear ice, the first noted on this flight, was picked up at 9700 feet at an indicated free-air temperature of 31° F (29° F static). At 9000 feet the indicated temperature was 33° F, (31° F static) and the ice melted off. Although the static temperature was below freezing, kinetic heating, due to the speed of the airplane, prevented the formation of ice at this level. Snow was present and also probably liquid water drops but they could not be identified. The airplane was then climbed to 11,000 feet and cruised at that level for a little over an hour while tests were made of some of the equipment on the airplane. During that time no ice formed. The indicated temperature was 30° F and steady snow continued throughout the period.

A slow descent was begun at about 11:15 a.m. near Duluth, Minn. A trace of ice was observed at 10,200 feet at an indicated air temperature of 31.5° F. The static freezing level was passed at 9300 feet and below that point steady rain and broken clouds were observed. The descent was continued to an altitude of 2600 feet and a static temperature of 33° F in an attempt to find the freezing rain zone. If the data used to draw the cross section of figure 2 had been available on the flight it would have been an easy matter to find freezing rain by going a little farther north, but since the north-south temperature gradient in the cold air was believed to be quite small, and since the entire area was warming up, the attempt to find freezing rain was abandoned and the airplane returned to Minneapolis. The temperature-height curve for this part of the flight is shown in figure 6.

DISCUSSION

The physical condition required for icing is the presence of liquid water drops at subfreezing temperatures. The meteorological problem, then, is to establish the location and extent of zones containing liquid water drops at temperatures below freezing. These zones may be divided into three classes: (1) areas of freezing rain; (2) clouds composed predominantly of water drops, and (3) clouds containing a high concentration of snowflakes or ice crystals together with liquid drops.

The freezing rain area was not reached on the flight but was located on the cross section by inference from the magnitude of the inversion observed near Duluth, and the radiosonde and surface observations at International Falls. Since the conditions required for freezing rain are generally well understood and can usually be forecast with fair reliability, only the icing zones above the frontal surface will be discussed here.

According to the Bergeron-Findeisen theory of the formation of precipitation, any large area of continuous precipitation is characterized by the presence of an abundance of snowflakes in the region above the freezing level. The coexistence of water drops and snowflakes for an appreciable time in a cloud at below freezing temperatures requires the existence of saturated conditions with respect to liquid water in the spaces between the snowflakes. Since the saturation vapor pressure is greater over water than over ice at temperatures below freezing, a condition of supersaturation must exist with respect to ice, causing deposition of vapor on the snow crystals. This results in a gradient of vapor pressure in the neighborhood of each snowflake and diffusion of vapor to the snowflakes. The only way that a condition of saturation with respect to liquid water can be maintained at points between the snowflakes, in spite of the diffusion of vapor to the snowflakes, is by continuous cooling and consequent lowering of the saturation vapor pressure with respect to both water and ice. This cooling is brought about by lifting of the air, and the rate of cooling is dependent upon the vertical component of the velocity. It appears, therefore, that a certain critical value of vertical velocity exists, as was suggested by Dr. Irving Langmuir of the General Electric Company Research Laboratory, which must be exceeded as a necessary condition for the coexistence of water droplets and snowflakes in a cloud.

This critical velocity is zero at the freezing level, since there the vapor pressures over ice and water are equal, and increases rapidly at temperatures below freezing.

In a warm front type of precipitation area such as is considered here, a large mass of air is lifted slowly by the action of horizontal convergence in the lower levels. This lifting is so gradual that the vertical velocities are generally much below the critical value. The air which moves upward through the freezing level usually contains liquid cloud droplets and may have fairly high liquid water content. As soon as the freezing level is passed, a depletion of the liquid water begins due to diffusion of vapor to the snowflakes, since it is assumed here that snowflakes are present in the subfreezing portion of the cloud system. Thus there is found, just above the freezing level, a transition zone in which snow flakes and liquid cloud drops exist together for a short time as the drops evaporate even though the vertical velocity may be less than the critical value. The vertical extent of the transition zone depends on the vertical velocity, the initial concentration of liquid water in the air as it reaches the freezing level, and the concentration of snowflakes. In this particular case, the observed upper limit of the transitional icing zone was 900 feet above the freezing level and the static air temperature at that point was 29° F. This explains the fact that all the icing observed on this flight occurred at static air temperatures of 29° F or higher. The observed patchy character of the icing in the transition zone was probably due to horizontal variations in the vertical velocity and in the initial concentration of liquid water.

In the situation where the air ascending through the freezing level does not contain cloud drops, while at the same time frozen precipitation falling through unsaturated air approaches (or reaches) the freezing level from aloft, then, the transitional icing zone does not exist and no icing can occur since no liquid water is present at below-freezing temperatures. This was the case on the first ascent. Rain alone, without cloud droplets was present below the freezing level and no icing was observed when passing through the freezing level from rain to snow. Liquid water was present in this case in the form of melting snow at temperatures just above freezing, but no icing was experienced. It is believed that the icing usually attributed to "wet snow" is due to liquid water drops which have been carried up through the freezing level and which form a film of freezing water on the airplane surfaces to which the dry snowflakes can adhere.

The speed of the airplane is an important factor in reducing the hazard in this kind of an icing zone since the temperatures are always only slightly below freezing. The kinetic heating effect prevents the formation of ice in the layer just above the static freezing level where the liquid water concentration is highest. On this flight the true airspeed was about 160 miles per hour, resulting in a kinetic heating effect of about 2° F in clouds. This reduced the maximum depth of the icing zone from 900 feet to about 300 feet. A speed of 200 miles per hour would have completely prevented icing, while if the speed had been reduced to 100 miles per hour, the effective depth of the icing layer would have been increased to 700 feet.

Vertical Velocities

In order to estimate the likelihood of icing conditions being encountered in warm-front-type precipitation areas at altitudes above the freezing level transition zone, a comparison was made of the approximate value of the critical vertical velocity and the velocities likely to occur in a cloud system of this type.

The icing data from the Mt. Washington Observatory, N.H., for the winter of 1945-46 were used to obtain an estimate of the critical vertical velocity. Since the average inclination of the wind at the Observatory is about 20° from the horizontal, the existence of a minimum wind velocity for ice formation in the presence of snow corresponds to the critical vertical velocity for the coexistence of liquid drops and snow. All cases of observations during periods of snowfall were plotted on a graph of wind velocity versus temperature. (See fig. 7.) The cases in which measurable icing was recorded were plotted as crosses and those without icing as circles. A scale of the vertical component of wind velocity was constructed based on an average inclination of 20°. These data are not very well distributed to establish the critical vertical velocity since average winds on Mt. Washington have vertical components much higher than the critical value. It is significant, however, that there were no cases of measurable icing with vertical wind components less than 450 feet per minute although there were

22 observations with vertical wind components below 450 feet per minute without icing. From these facts it may be inferred that vertical velocities of the order of 400 feet per miuute or more are required for the continued existence of liquid cloud drops in the presence of moderate snow at temperatures appreciably below freezing.

The approximate value of the actual vertical velocities likely to occur in warm-front-type precipitation areas may be estimated from the horizontal divergence of the wind velocity or from the rate of precipitation. In reference 1 it is shown that a mean horizontal divergence of 10^{-5} per second between sea level and 10,000 feet produces a vertical velocity of 3.5 centimeters per second (6.9 feet per minute) at the 10,000-foot level. In the weather map of 0630 GCT, March 31, 1945, which is presented as an example in reference 3, a warm-front precipitation area similar to the one discussed in this report covers the area embracing Indiana, Ohio, and Lake Erie. Also presented in reference 1 are charts, based upon pilot balloon data, depicting the distribution of horizontal divergence at 5,000 feet and 10,000 feet for 0400 GCT, March 31, 1945. The values of divergence, as shown by these charts for the area of Indiana, Ohio, and Lake Erie, fall in the range from 10^{-5} to 4×10^{-5} per second corresponding to vertical velocities from 7 to 28 feet per minute at 10,000 feet. While it is realized that there may be considerable differences in vertical velocity in different warm-front precipitation areas, these data should at least suggest the order of magnitude to be expected in such situations.

Reference 1 also includes a calculation of the vertical velocity required to produce the observed precipitation rate in a general precipitation area. It was found that the average vertical velocities over an area 150 miles square apparently ranged from 1 centimeter per second to at least 15 centimeters per second (2 to 30 ft per min). Since these two calculations give results of the same order of magnitude, it would appear reasonable to accept these values as typical for warm-front precipitation areas. On the basis of these considerations, a vertical velocity of 50 feet per minute has been selected as a probable maximum to be expected in a warm-front precipitation area.

Comparison of the probable actual vertical velocity with the critical velocity as determined from the Mt. Washington data shows that the critical velocity is much larger than the actual velocity. It follows, therefore, that stable, precipitating, warm-front-type cloud systems do not in general contain liquid water drops at below freezing temperatures except in the immediate vicinity of the freezing level.

This conclusion supports the theoretical model of the precipitating stratoform cloud structure proposed by Findeisen (reference 2) rather than that given by Byers (reference 3) which includes a large region of mixed water drops and snow crystals above the warm front surface giving rise to the supposition that severe icing conditions exist within this region. The observations made on this flight and the theory given here to interpret them do not support, in fact directly contradict, the Byers model. Further observations are desirable to determine the validity of this model since it has been used as a basis for the discussion of icing in recent text books in meteorology.

CONCLUDING REMARKS

While it is realized that it is hazardous to draw conclusions from observations of a single case, the consistent theoretical interpretation of the observed conditions is believed to justify the following generalization:

In large areas of uniform precipitation in the absence of marked orographic influences, the icing zones are limited to the freezing rain area, if any, and a shallow layer of mixed snow and cloud drops just above the freezing level.

Ames Aeronautical Laboratory
National Advisory Committee For Aeronautics
Moffett Field, Calif., June 1947.

REFERENCES

1. Houghton, H. G. and Austin, J. M.: A Study of Non-geostrophic Flow With Applications to the Mechanism of Pressure Changes. Journal of Meteorology, vol. 3, no. 3, September 1946, pp. 57-77.

2. Findeisen, W.: Meteorological-Physical Limitations of Icing in the Atmosphere. NACA TM No. 885, 1939.

3. Byers, Horace Robert: Synoptic and Aeronautical Meteorology, McGraw-Hill Book Co., Inc., 1937, p. 234.

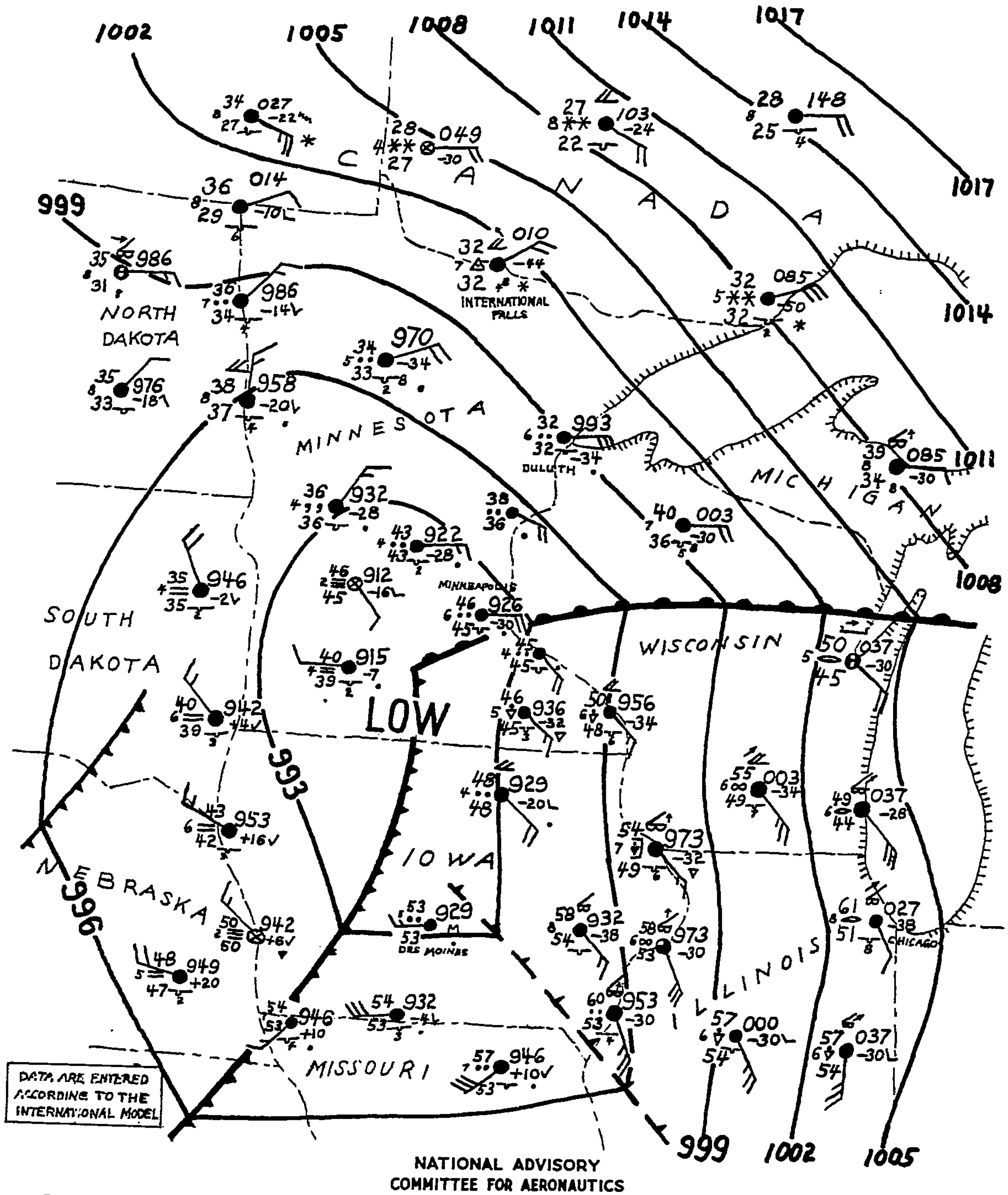

FIGURE 1 - WEATHER MAP OF UPPER MISSISSIPPI VALLEY; 9:30 AM, MARCH 15, 1945

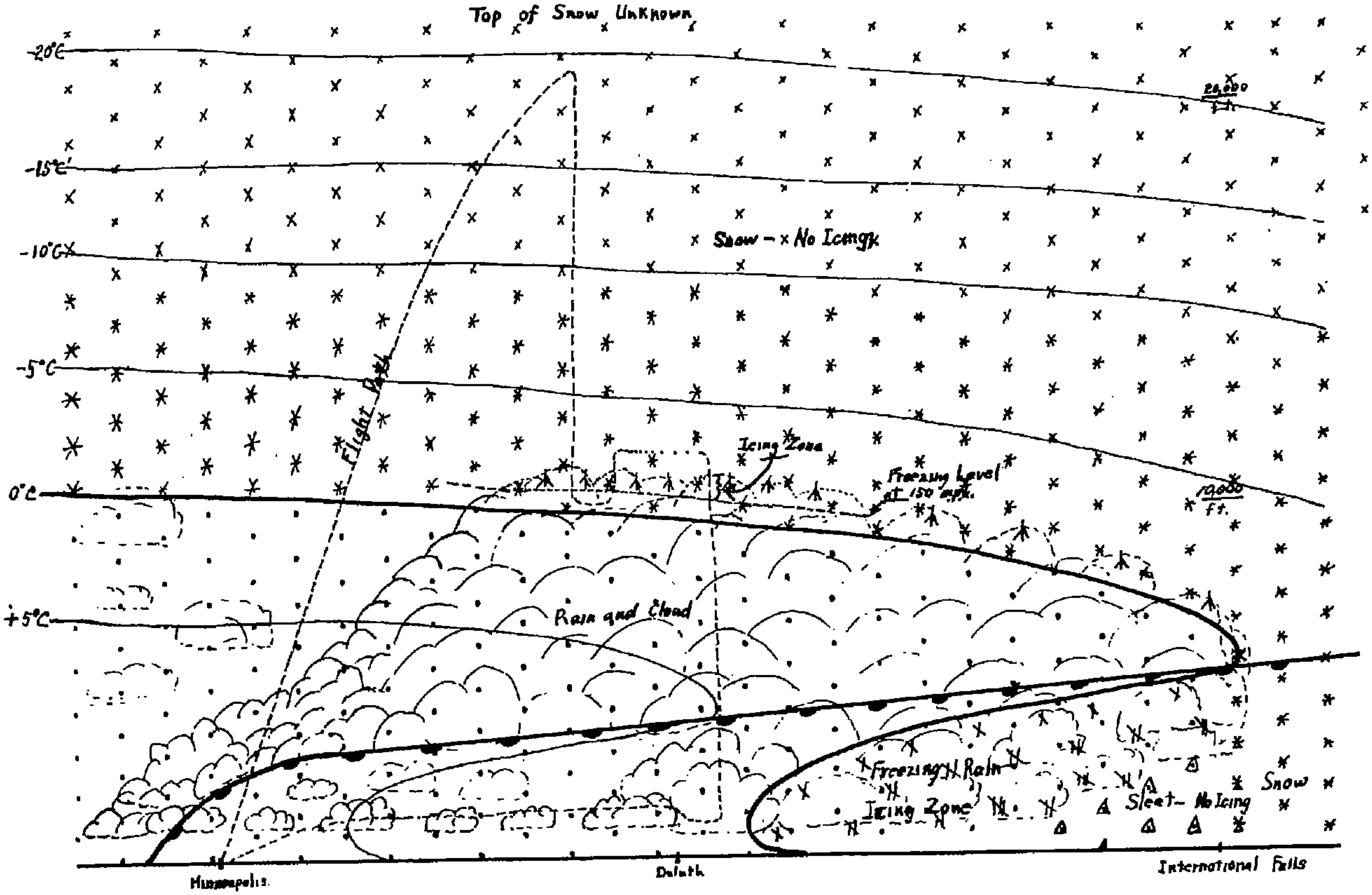

FIGURE 2.— CROSS SECTION OF WARM FRONT CLOUD SYSTEM OVER MINNESOTA ON MARCH 16, 1945 AT ABOUT 9:30 A.M.

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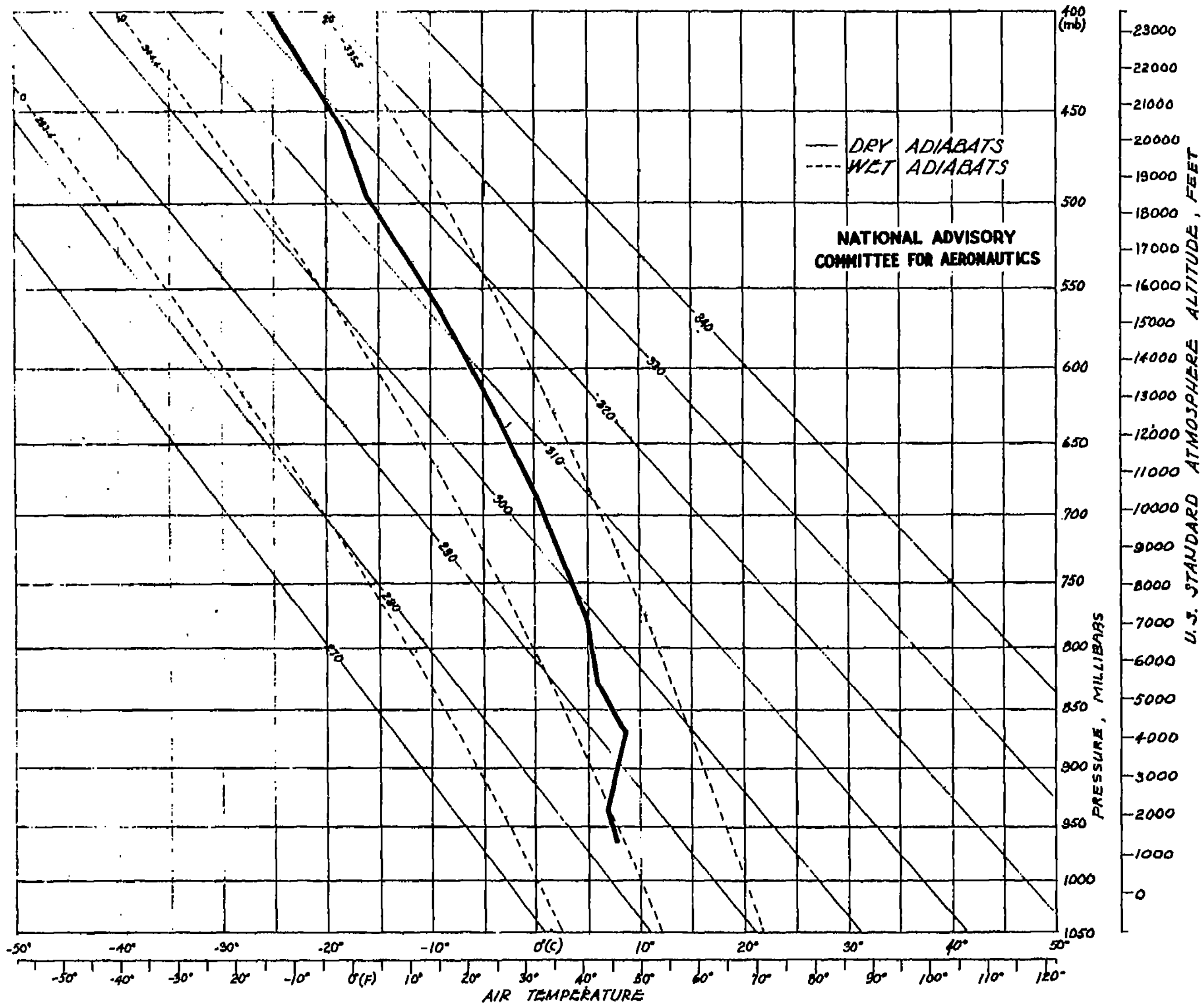

FIGURE 3.- DATA OBTAINED FROM RADIOSONDE ASCENT AT ST. PAUL, MINNESOTA ON MARCH 15, 1945 AT 9:00 AM

Fig. 3

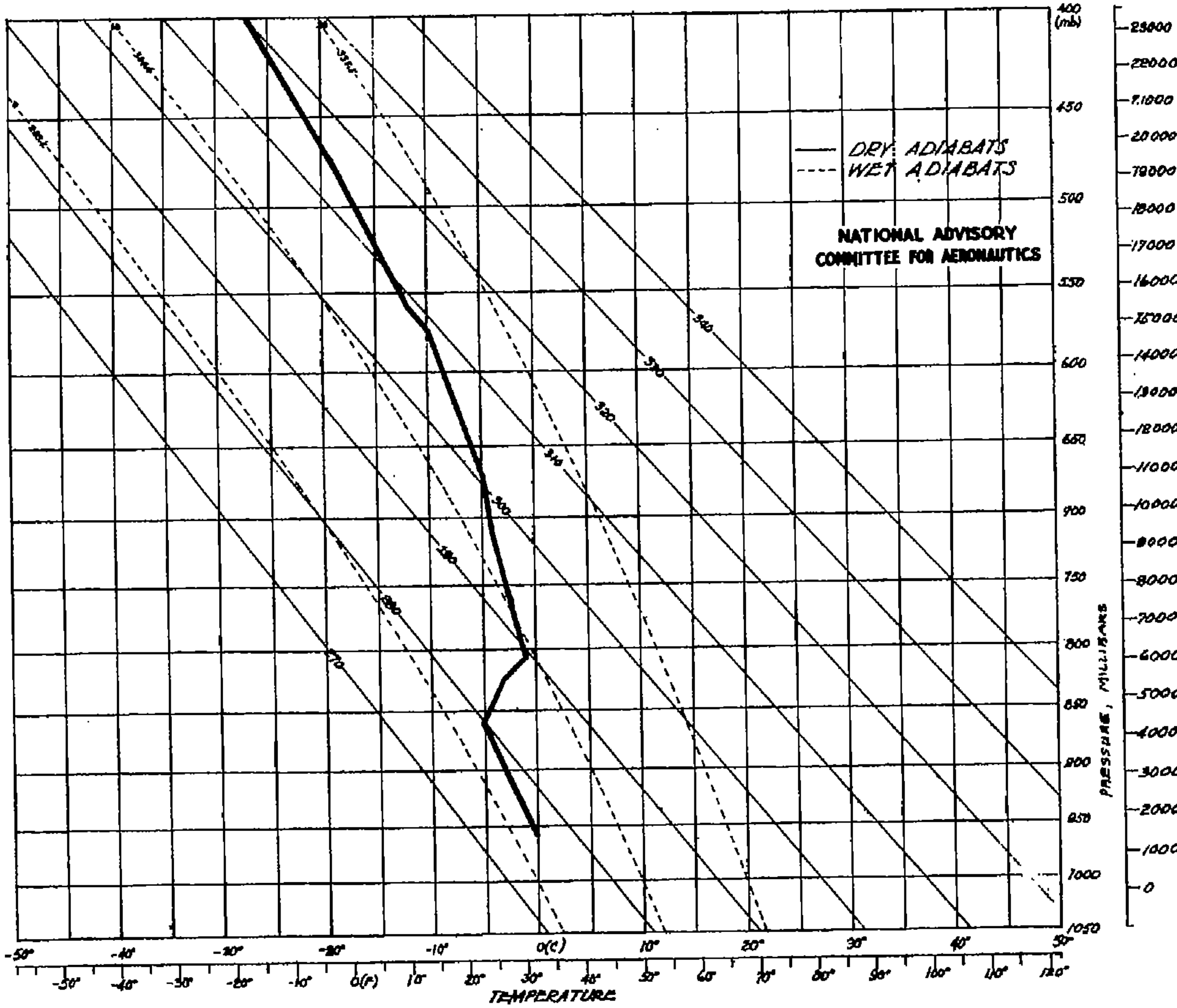

FIGURE 4 - DATA OBTAINED FROM RADIOSONDE AT INTERNATIONAL FALLS, MINN. ON MARCH 15, 1945 AT 9:00 AM.

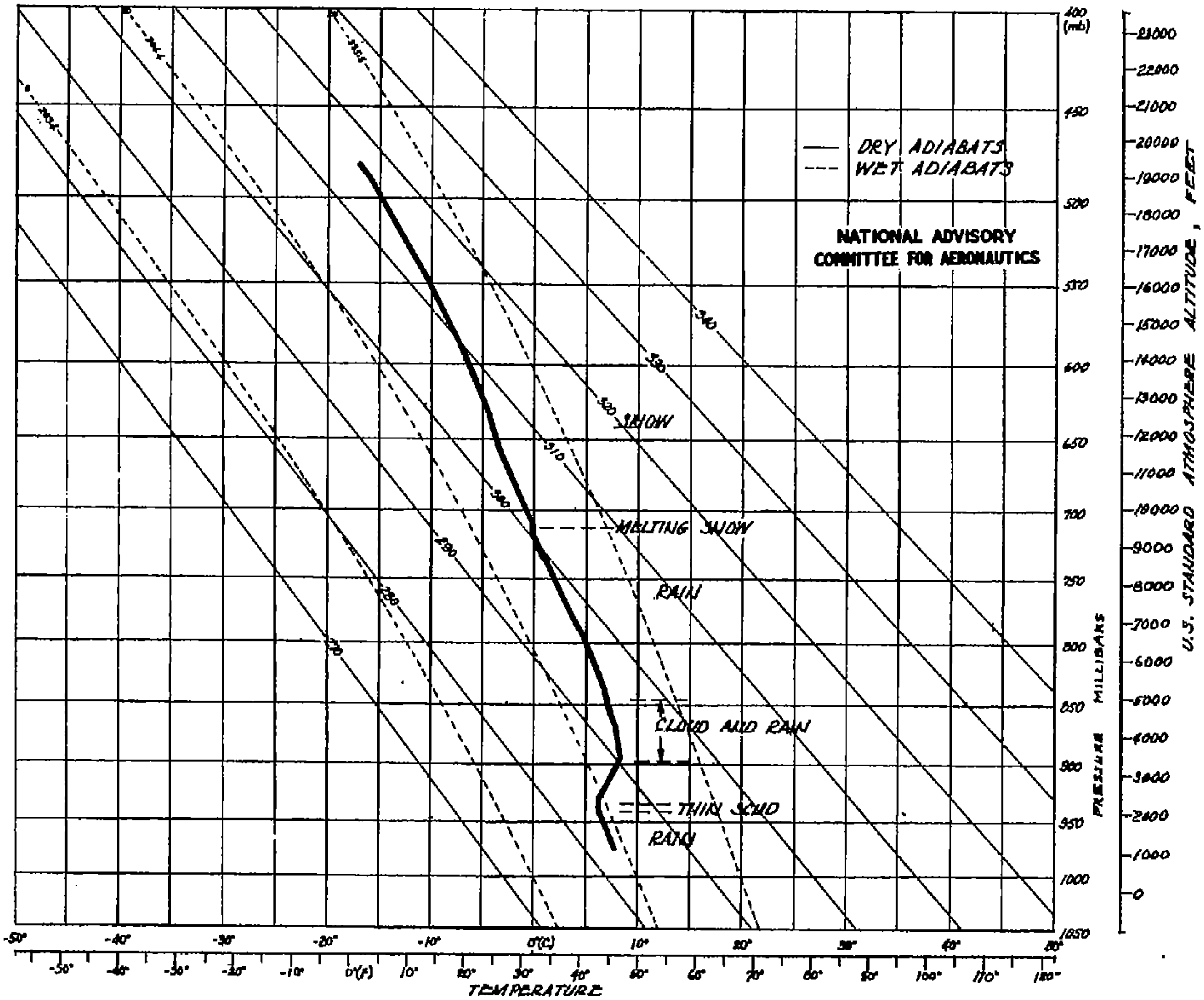

FIGURE 5 - DATA OBTAINED FROM AIRPLANE OBSERVATIONS DURING ASCENT BETWEEN MINNEAPOLIS & DULUTH, MINN. ON MARCH 15, 1945 FROM 8:25 TO 9:20 AM.

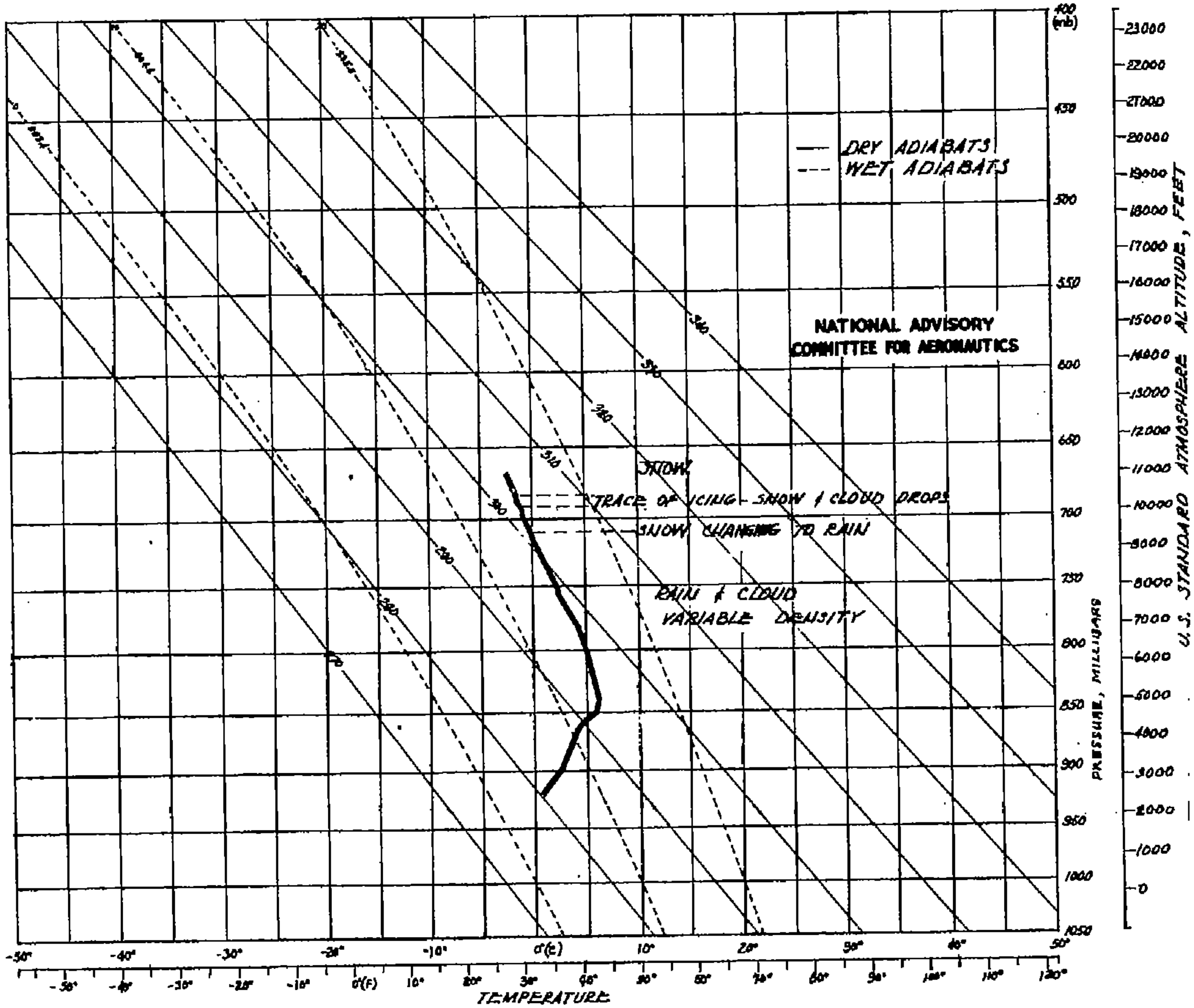

FIGURE 6 - DATA OBTAINED FROM AIRPLANE OBSERVATIONS DURING DESCENT NEAR DULUTH, MINN. ON MARCH 15, 1945 FROM 11:15 TO 11:45 AM.

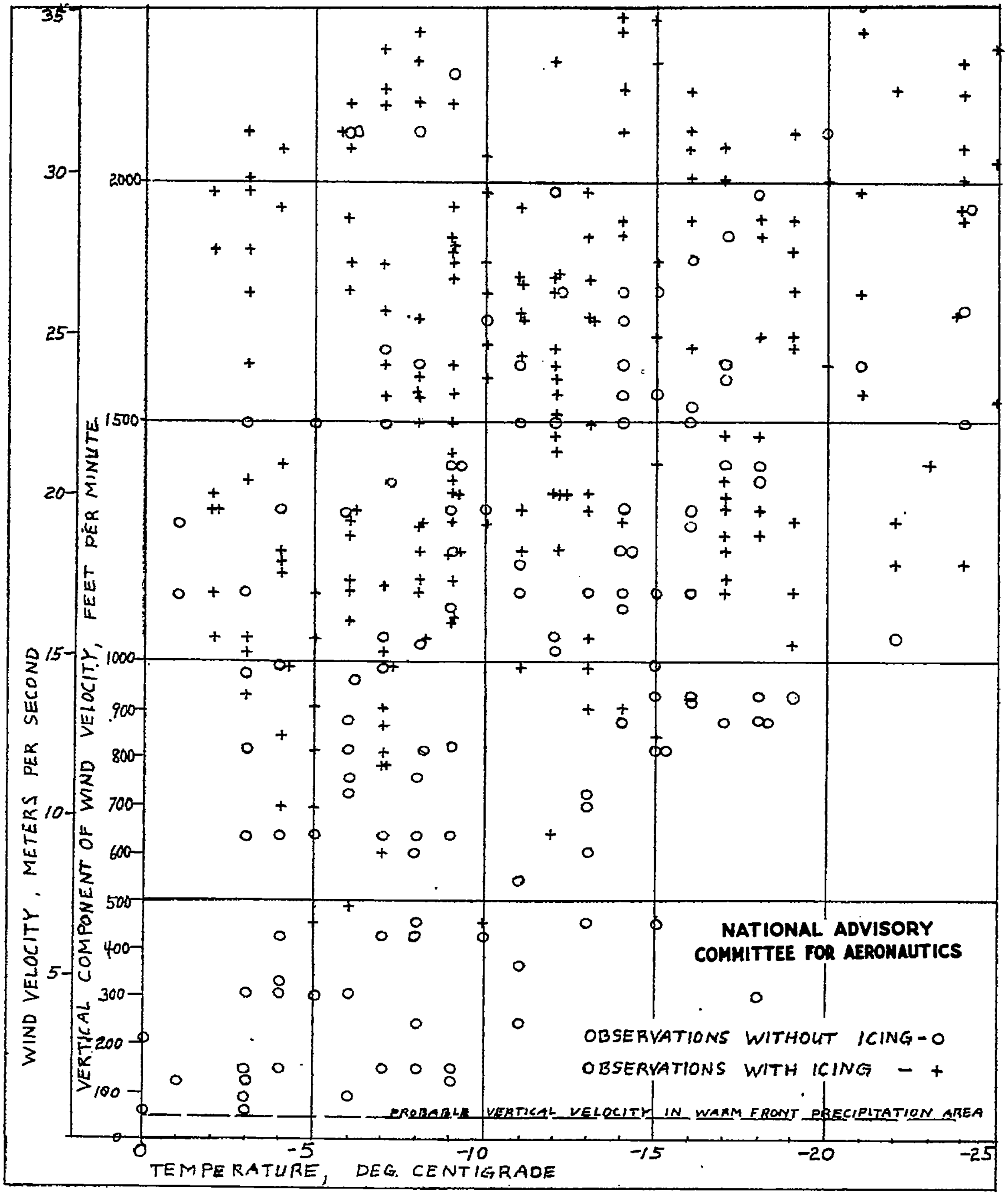

FIGURE 7. - MOUNT WASHINGTON ICING OBSERVATIONS DURING SNOWFALL.